Punch Plastic Deformation Pipe Cladding (PPDPC) as a Novel Tube Cladding Method

Mohammadreza Baghaei, Ghader Faraji*

Department of Mechanical Engineering, University of Tehran, Tehran 11155-4563, Iran

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ABSTRACT

This study presents a new mechanical tube cladding process named punch plastic deformation pipe cladding (PPDPC) based on local deformation by pressing a punch into the inner layer of the bimetal tube. To investigate the capability of the process, stainless steel tube (as the inner layer) is bonded to a carbon steel pipe (as the outer layer) to fabricate a bimetal pipe. Shear punch tests were used to evaluate the bond strength between layers. Also, optical microscopy (OM) was employed to investigate the bonding interface. Experimental results showed an excellent bonding at the interface of two layers. Shear punch test results showed that the bonding achieved from this new method is stronger than the conventional thermo-hydraulic cladding method. This process is influenced by several parameters including punch diameters, punch nose radius and the friction coefficient between the punch and cladding tube. The effects of these parameters were evaluated by finite element (FE) analysis. Good bonding, simplicity, lower cost and no change in the microstructure of the main pipe (outer layer) are the major advantages of this process.

1. Introduction:

In pipes or tubes, when the fluid passing through is corrosive, the cladding can protect the pipe or tube from corrosion. In the cladded pipes, the inner layer made from corrosion resistance material with at most some millimeters thick, meanwhile the cheaper outer pipe provides the required strength and toughness to maintain the mechanical integrity. The study about the double-layered tubes began in the 1980's, and it was an optimum solution to the most demanding requirements of strength, corrosion resistance and cost-effectiveness [1]. There are several methods for bonding the main pipe and the cladding layer. These methods are divided into two categories of mechanical and metallurgical methods. As a mechanical method extrusion [2,3] can be pointed out, multi-billet extrusion [4], explosive bonding [5,6], diffusion bonding [7,8], centrifugal casting [9], conventional or asymmetrical roll bonding [10,11] and laser cladding [12]. Besides, thermo-hydraulic fit method and hydraulic expansion method [1,13,14] are also classified as mechanical methods. New studies being done on new methods of ball attrition [15], high-pressure tube twisting (HPTT) [16], and spin bonding (SB) [17,18]. Using bimetal pipes is economical because the main pipe is much cheaper than the protective layer. Nevertheless, each method has its limitations. Metallurgical methods can make residual stress that causes stress corrosion cracking in bonding interface [13]. For explosive bonding and extrusion, the low cladding thickness is a restriction [17]. In mechanical methods, in addition to the required power and force, the expensive and complicated

* Corresponding author:
E-mail address: ghfaraji@ut.ac.ir

equipment are relatively needed [18,19]. In hydro-mechanical methods, sealing is crucial and challenging. In general, mechanical methods have higher production rates and lower construction costs than metallurgical methods [20-21]. In hydraulic expansion method, the internal pressure applied to the total length of pipe and caused deformation in the total length of pipe. To overcome the disadvantageous of the conventional methods, in this study a new simple mechanical method that is presented to produce bimetal tubes. The method is applied to produce a stainless steel-carbon steel bimetal tube.

2. Principle of PPDPC Process

PPDPC process is a mechanical tube cladding procedure shown in Fig. 1. Bimetal tube consist of the outer thick carbon steel seamless, or welded tube bears the load, and the inner thin stainless steel one have anti-corrosion properties. Before the process, the inner face of the outer pipe and the outer face of the inner tube were cleaned carefully by Alkaline wire brushing. After cleaning, the inner tube is placed into the outer pipe as shown in Fig. 1(a). During the process, the punch is pressed into the inner tube. So, the inner tube is plastically deformed while the outer pipe is elastically deformed as shown Fig. 1(b). At the end of the process, the punch exit from the other side of the tube as shown in Fig. 1(c). With increasing deformation in the cladding tube, deformation occurs elastically in the main pipe. Punch diameter must be designed to avoid plastic deformation of the main pipe. After passing through the tube, reversible strains reverse and creates residual contact pressure. The process was performed at room temperature. Due to the simplicity of the process, manufacturing by this method rate is higher than the former methods.

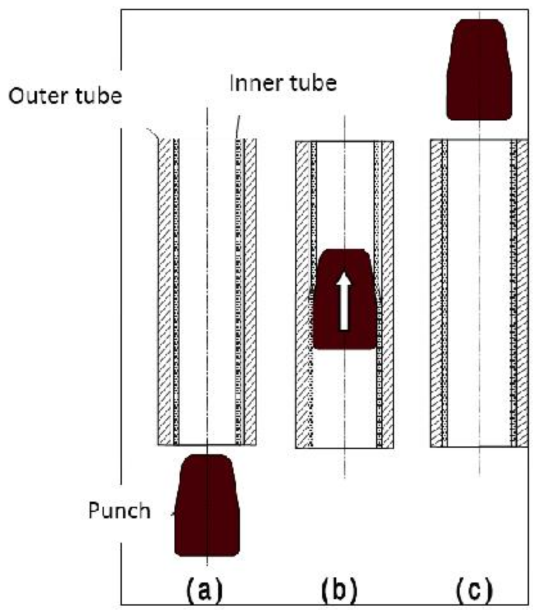


Fig 1. Schematic of PPDPC process (a) at the start (b) during deformation of the inner tube (c) cladded bimetal tube at the end of the process.

3. FE and experimental procedures

The commercial FE code ABAQUS/Explicit was used to perform the numerical simulations. A 3D model was employed, where the geometrical dimensions and mechanical properties of specimens were the same as those of the experiment. Tubes modeled as deformable and punch and dies considered as rigid parts. Quad dominated element shape selected and structured technique adapted for meshing. Totally 2500 and 7230 3D elements were used to mesh the inner and outer tubes, respectively. The Coulomb friction and penalty method were used to model the contact between the punch and the inner tube. Coulomb friction coefficient was assumed to be 0.05. The support and the mandrel were modeled as discrete rigid parts. To check the effects of the process parameters, different values for the punch fillet radius and friction coefficient were considered in the numerical analysis.

The material used in this study for the outer and inner tubes were carbon steel API5LX52 and stainless steel 316L, respectively. Inner and outer diameter of stainless steel tube was 77 mm and diameter of 87 mm. Also, inner and outer diameter of carbon steel tube was 96 mm and diameter of 114.3 mm. The length of the both tubes was 500 mm. The physical properties of API 5L X52 and SS316L were shown in Table 1. The punch was fabricated from tool steel and then hardened to 58 HRC. The geometrical parameters and manufactured punch were shown in Fig. 2 and Table 2. After hardening, grinding was used to decrease friction effects.

Table 1. Main pipe and cladding tube material properties.

Material	API 5L X52	SS316L
Young's modulus (E)	7800 Kg/m^3	7800 Kg/m^3
Poisson's ration (ν)	210 GPa	196 GPa
Density (ρ)	0.30	0.29

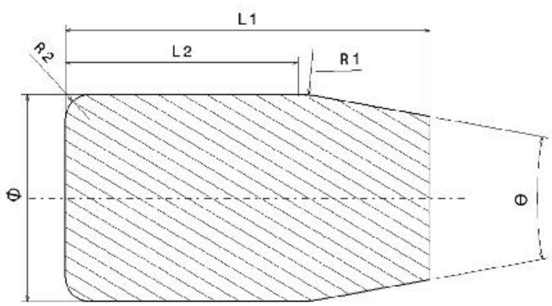


Fig 2. Manufactured punch and its dimensions

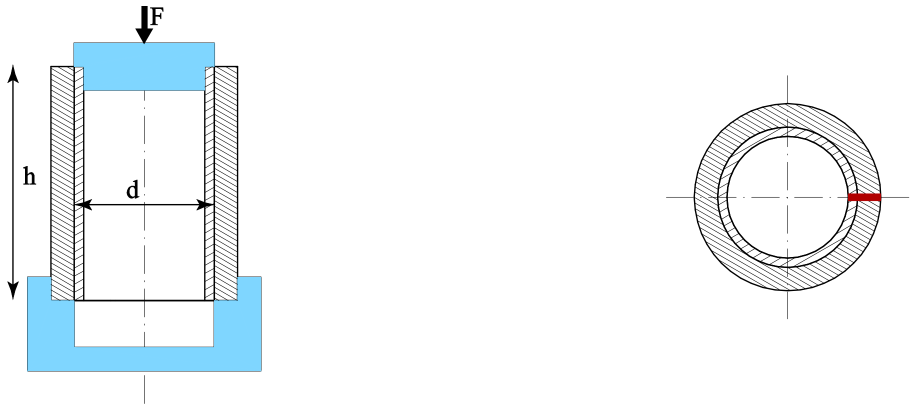
Table 2. Punch dimensions value

Parameter	θ	R1	L1	L2	R2	Φ
Value	20°	100 mm	150 mm	90 mm	10 mm	87 mm

Before starting the process, the inner surface of the outer tube and the outer surface of the cladding tube must be cleaned by acetone. Then, wire brushing with a 52 mm diameter stainless steel cylindrical brush at the rotational speed of 2000 rpm was performed. The PPDPC process was done at a punch speed of 250 mm/min at room temperature using a 100 ton hydraulic press. For comparison, the tubes were cladded by another process named conventional thermo-hydraulic fit method.

After cladding, the cladded bimetal tube was cut in perpendicular to axis direction to study the shear strength, microstructural evolution and microhardness tests. Optical microscope (OM) was used to study microstructural evolution after polishing and etching with Nital etchant. Microhardness of the sample was measured using Vickers microhardness machine according to ASTM E384-11 with a load of 300 gf applied for 10s. Shear punch test was performed by the punch tool as shown in Fig. 3 at room temperature. The test stopped at the punch stroke of 10 mm. Meanwhile, the peak load was recorded. The shear strength of the joint can be calculated by Eq. 1, where τ is the shear strength, F is peak laod, *A* is the shear area at the interface, *d* is the diameter of shear area at the interface and *h* is the height of the sample.

$$\tau = \frac{F}{A} = \frac{F}{\pi d h} \quad (1)$$



(a) (b)

Fig 3. (a) Shear punch test tools, (b) microhardness and microstructure measurment position.

4. Results and Discussion

Fig. 4(a) show the assembled pipes with process punch at the start of the process. A cross-sectional view of the processed bimetallic pipe was shown in Fig. 4(b). As shown, a sound joint with good surface appearance and a good bonding at the interface was formed by PPDPC process. The OM micrograph of the bimetal pipe interface was shown in Fig. 5. It could be seen that a good bonding was achieved between SS316L and carbon steel tubes after PPDPC process.

(a) (b)

Fig 4. (a) A die setup including assembled tubes and process punch at the start of the process, (b) a cross section of processed bimetallic pipe.

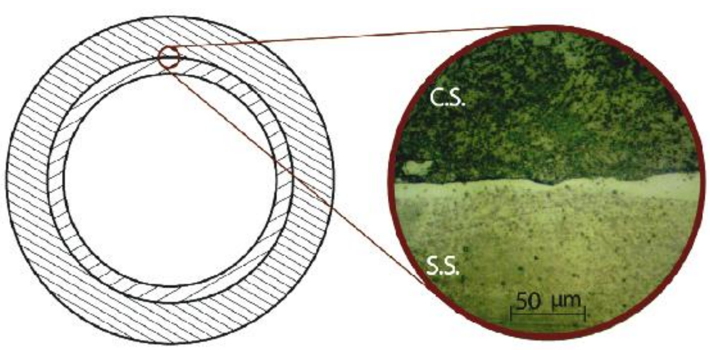


Fig 5. OM micrograph of the interface between stainless steel and carbon steel tubes.

Figure 6 shows the microhardness variation along the thickness of the bimetal cladded pipe processed by PPDPC method. It shows that the hardness variation in carbon steel side is approximately linear and equal to its initial value. This means that the mechanical properties and microstructure of the outer tube does not change during PPDPC. However, in stainless steel, the hardness value is greater than the initial value because of the plastic deformation and the subsequent change in the microstructure [23]. As is known, the microstructure and grain size of the metal is changed by plastic deformation [24, 25].

It was revealed from the shear punch test that the threshold force required to move the pipe is equal to 7900 kgf for the cladded pipe made by PPDPC and 3600 kgf for the cladded pipe made by thermo-hydraulic fit method. It shows that the PPDPC method produce bimetal tube with strong bonding between two layers. A higher level of shear force also verified a good bonding of CS and SS bimetal pipe processed by PPDPC.–

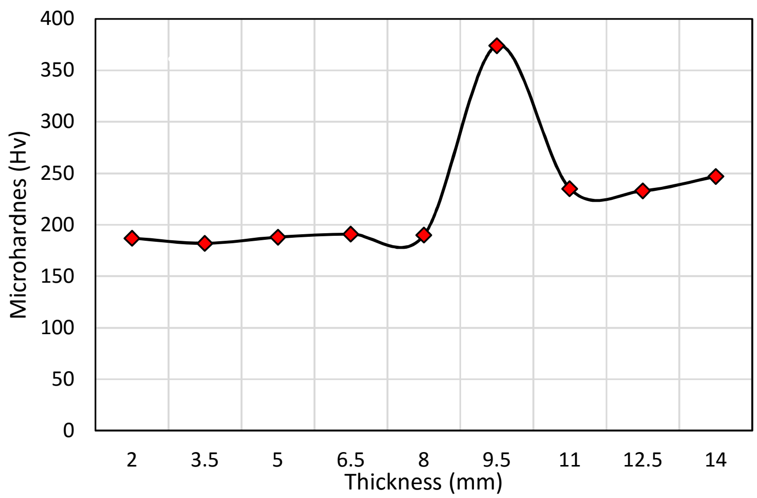


Fig 6. Microhardness variation along the thickness of the processed bimetal tube (left: carbon steel, Right: stainless steel).

Fig. 7 shows the FE calculated punch force for various friction coefficients. As shown in this figure, the punch force rises to a specified level and remains relatively constant by the end of the process in all cases. As is seen, by increasing the friction coefficient, the force required increases.

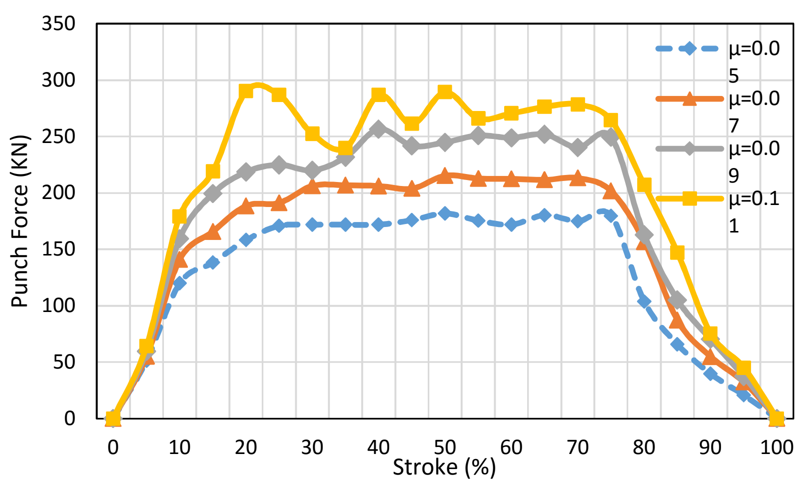


Fig 7. Punch force versus stroke curves in various friction coefficient.

Figs. 8(a) - (e) show the equivalent plastic strain contours of the stainless steel inner tube after PPDPC processing with different punch fillet radius of 20 mm, 40 mm, 60 mm, 80 mm and 100 mm, respectively. In all cases, the friction coefficient was 0.05. It could be seen that the smaller punch radius led to higher equivalent plastic strain values. This may lead to a refined microstructure and smaller grain size.

As is known, the contact pressure plays a main role in bimetal tube cladding. The contact pressure may be an important factor for achieving a good bonding between layers. Higher the contact pressure leads to better interface properties. Figs. 9(a)-(e) show the contact pressure between the outer and inner tubes for various inner tubes with inner diameters of 74 mm to 80 mm during PPDPC. These figures show that the contact pressure is increased by decreasing the initial diameter of the inner tube.

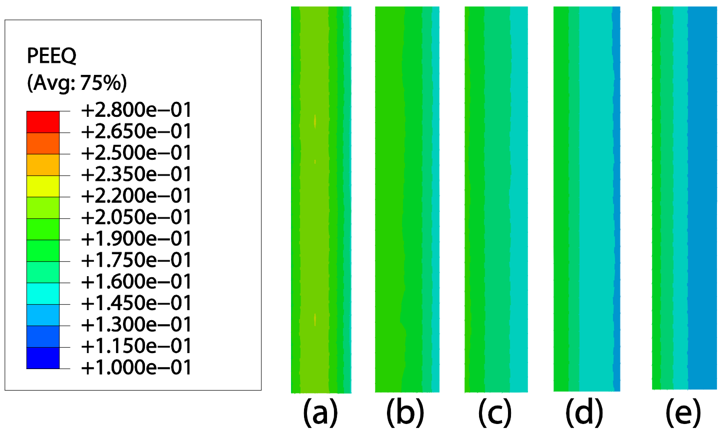


Fig 8. Equivalent plastic strain contours of the inner tube in PPDPC process by different punches with punch fillet radius of 20 mm(a), 40 mm(b), 60 mm(c), 80 mm(d) and 100 mm(e).

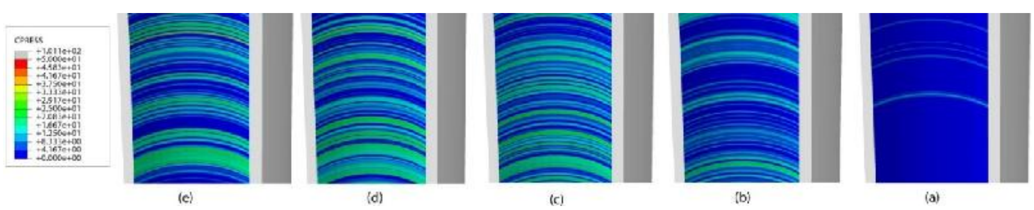


Fig 9. (a)-(e) Contact pressure contour between the outer and inner tubes for various inner tubes with inner diameters of 74 mm to 80 mm.

5. Conclusions

A new tube cladding method entitled punch plastic deformation pipe cladding was presented. The results showed that two dissimilar tubes can be successfully bonded using the punch plastic deformation pipe cladding method. Unlike weld cladding, PPDPC does not create inappropriate mechanical and chemical changes in the base tube material. Good bonding at the interface between two materials is a result of applying this new process. Effect of friction coefficient, punch fillet radius, and initial diameter of the cladding tube was evaluated. An increase in the friction coefficient leads to an increase in the required force. Smaller punch fillet causes more plastic strain in the cladding or inner tube. Choosing inner or cladding tube diameter larger than an optimum size can affect the contact pressure value and bonding quality.

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